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THE STUDY OF RELAXATION OF BOLTS
AT HIGH TEMPERATURES

-

C. A. Allsopp

THE STUDY OF RELAXATION OF BOLTS
AT HIGH TEMPERATURES

by


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Lieutenant Commander, United States Navy

Submitted in partial fulfillment
of the requirements
for the degree of
MASTER OF SCIENCE

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1948

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the thesis requirements for the degree of
MASTER OF SCIENCE

from the
United States Naval Postgraduate School.



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PREFACE

Since 1941 the Naval Experiment Station has been making relaxation tests. From December 1947 through May 1948 the author collected and analyzed this data for the purpose of finding a relationship between initial stress, time and stress. This work was carried on at the United States Naval Experiment Station and at the United States Naval Postgraduate School.

Acknowledgements are due to Dr. G.H. Lee and Dr. F.L. Coonan of the United States Naval Postgraduate School for their supervision of the project, to Mr. A.M. Bruce and the metallurgical staff of the United States Naval Experiment Station for their assistance in running the tests and making information available to the author.

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TABLE OF SYMBOLS AND ABBREVIATIONS

σ	Stress in pounds per square inch
σ_0	Initial Stress in pounds per square inch
σ_r	Reduced stress in pounds per square inch
psi.	Pounds per square inch
F	Fahrenheit
E	Young's Modulus
ϵ	Young's Modulus per degree Fahrenheit
T	Time in hours
θ	Temperature in degrees Fahrenheit
β	Derivative of the rate of relaxation with respect to temperature
M	Mass
L	Length
π	Pi
°	Degree
VS	Versus
C	Carbon
S	Sulphur
P	Phosphorous
Mn	Manganese
Si	Silicon
Cr	Chromium
Mo	Molybdenum
Ni	Nickel
V	Venadium
W	Tungsten

ULT. STR.	Ultimate Strength
%	Percentage
ELONG.	Elongation
Δ	Delta
D.C.	Direct current
X	Magnification

I INTRODUCTION AND SUMMARY

The increasing number of naval projects in the high temperature field has made the behavior of bolts under high temperatures a matter of concern to the Navy. Much experimental work has been done in determining the creep resistance of metals. However for the design engineer, the creep rate for a given bolt material is at best an unhandy piece of information. Furthermore the creep test supposes a constant stress with plastic deformation. In the case of the bolt, one has instead an initial elongation of the bolt caused by the initial stress; then creep tends to further elongate the bolt, but instead of causing elongation part of the bolt load is removed. The bolt is said to have relaxed, and has the same initial elongation(see appendix for mathematical treatment).

Six years ago the Naval Experiment Station designed and set up a relaxation machine intended to duplicate the above described bolt relaxation phenomenon. The test specimen was loaded giving an initial elastic deformation. When creep tended to further elongate the specimen, sufficient load was removed to return the specimen to the initial elongation. The primary purpose of these tests was to determine how much different bolt materials relaxed under constant temperature. The emphasis in these tests was placed on the final relaxation stress as an indicator of the usefulness of the bolt material. No attempt was made to analyze the data for the purpose of de-

termining if any specific relationships existed between time; temperature, and stress for the given materials.

A major portion of this thesis was the collection and analysis of existing data to find such a relationship. As the original tests were not performed for this purpose the author performed 6 relaxation tests in order to obtain desirable initial conditions.

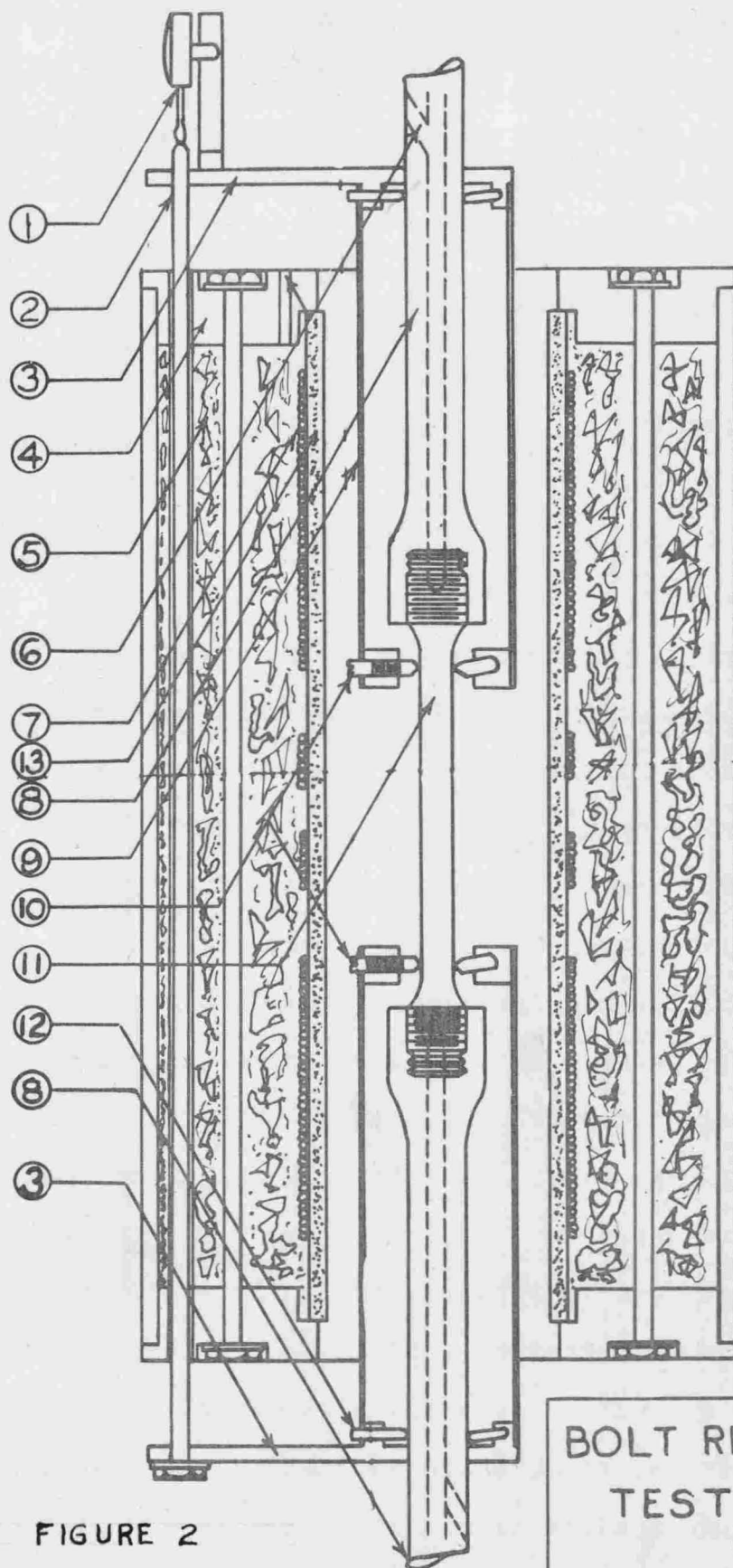
The project also included a detailed description of the test equipment. A study was made of existing literature on the subject (see bibliography). Finally a portion of the thesis was devoted to the metallurgical factors affecting bolt relaxation, conclusions, and suggestions for carrying on further analyses.

II DESCRIPTION OF TEST EQUIPMENT

1 Description of Relaxation Test Machine

Essentially the test apparatus consists of a lever system, an oil filled tank, and a furnace enclosed test specimen. The weight of the oil-filled tank thru the lever system and adapters applies a load to the specimen. The lower end of the specimen and its adapter are anchored. To maintain their alignment both adapters are lightly supported by means of the round ended adapter holding pins. The upper adapter, attached to the lever system, rises as the specimen elongates. The amount of elongation is measured between two points four inches apart by means of the specimen holding points. The lower holding points, lower inconel cylinder and its end piece, and vertical inconel rod are at all times stationary. When the specimen elongates the upper holding points, upper inconel cylinder and its end piece, and strain gauge rise. Thus the arm of the strain gauge would tend to be raised above the end of the inconel rod. However a spring keeps it in contact with the top of the rod. The movement of the strain gauge's arm to maintain the contact actuates the pointer on the dial of the gauge. The dial is divided into 100 divisions, one division equaling .0001 inches.

After the initial elongation caused by the application of the load, the dial is set so that the pointer is one and a half divisions from an electrical contact. The contact surfaces are silver or platinum. Thus when the specimen elongates .00015 inches the contact is closed. This opens a



1. STRAIN GAUGE (TRAN-
SITE BASE).
2. INCONEL ROD.
3. CYLINDER END
PIECES (ALUMINUM).
4. FURNACE END
PIECES (TRANSITE).
5. DIATOMACEOUS
EARTH FILLER.
6. THERMOCOUPLE
INLET.
7. HEATING ELEMENT
(NICHROME).
8. ADAPTER (N-155).
9. INCONEL CYL-
INDER.
10. SPECIMEN HOLD-
ING POINTS (K-42 B).
11. SPECIMEN.
12. ADAPTER HOLD-
ING PINS.
13. ALUNDUM LINER.

BOLT RELAXATION TEST FURNACE

DRAWN BY C.A. ALLSOPP

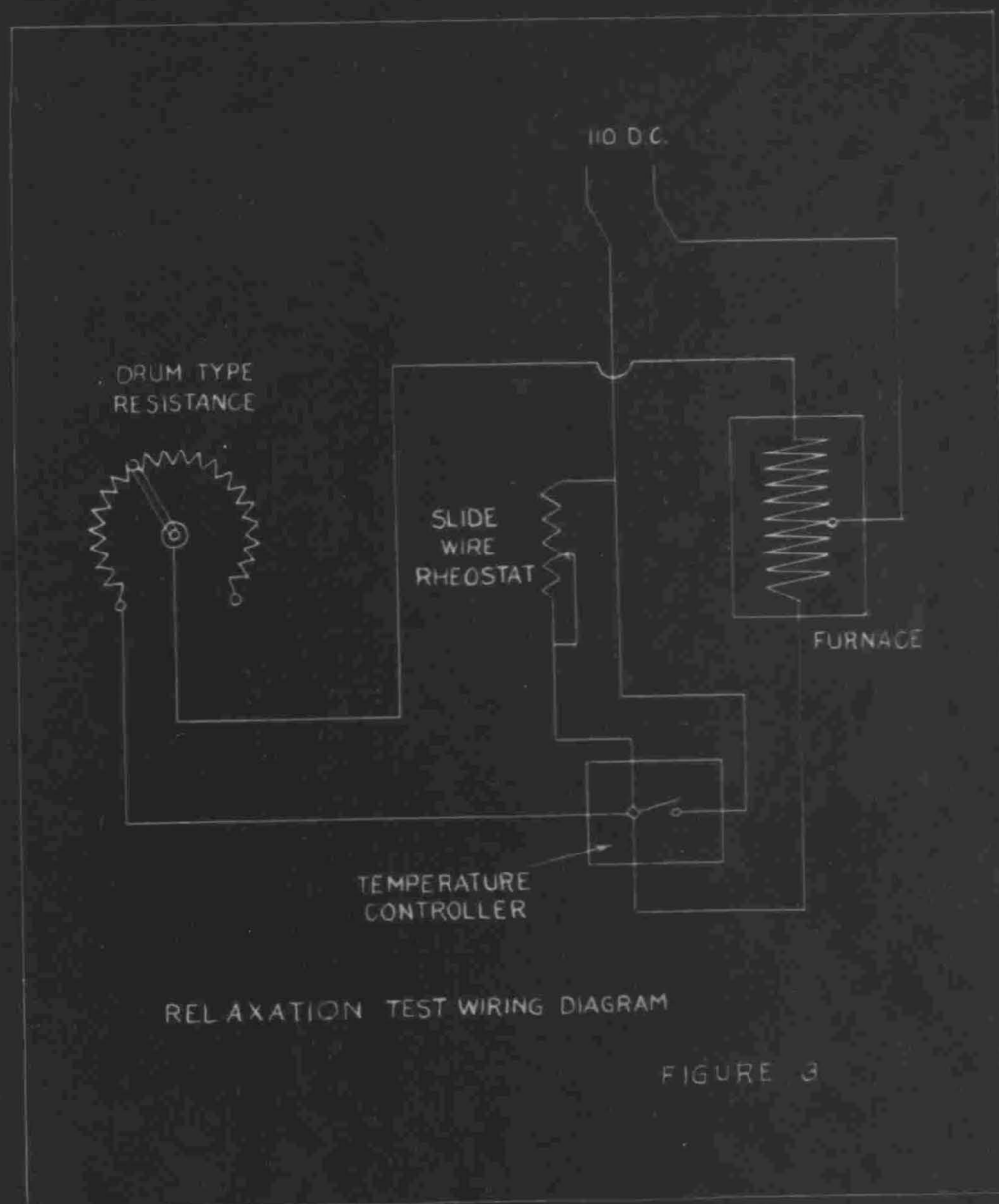
FIGURE 2

magnetic valve allowing oil to drain from the tank until the specimen's elongation is reduced to less than .00015 inches; the contact is broken and the process repeats itself. To find the amount of relaxation at any time, one weighs the amount of drained oil. This value can then be multiplied by a constant to give the number of pounds per square inch that have been removed from the initial stress.

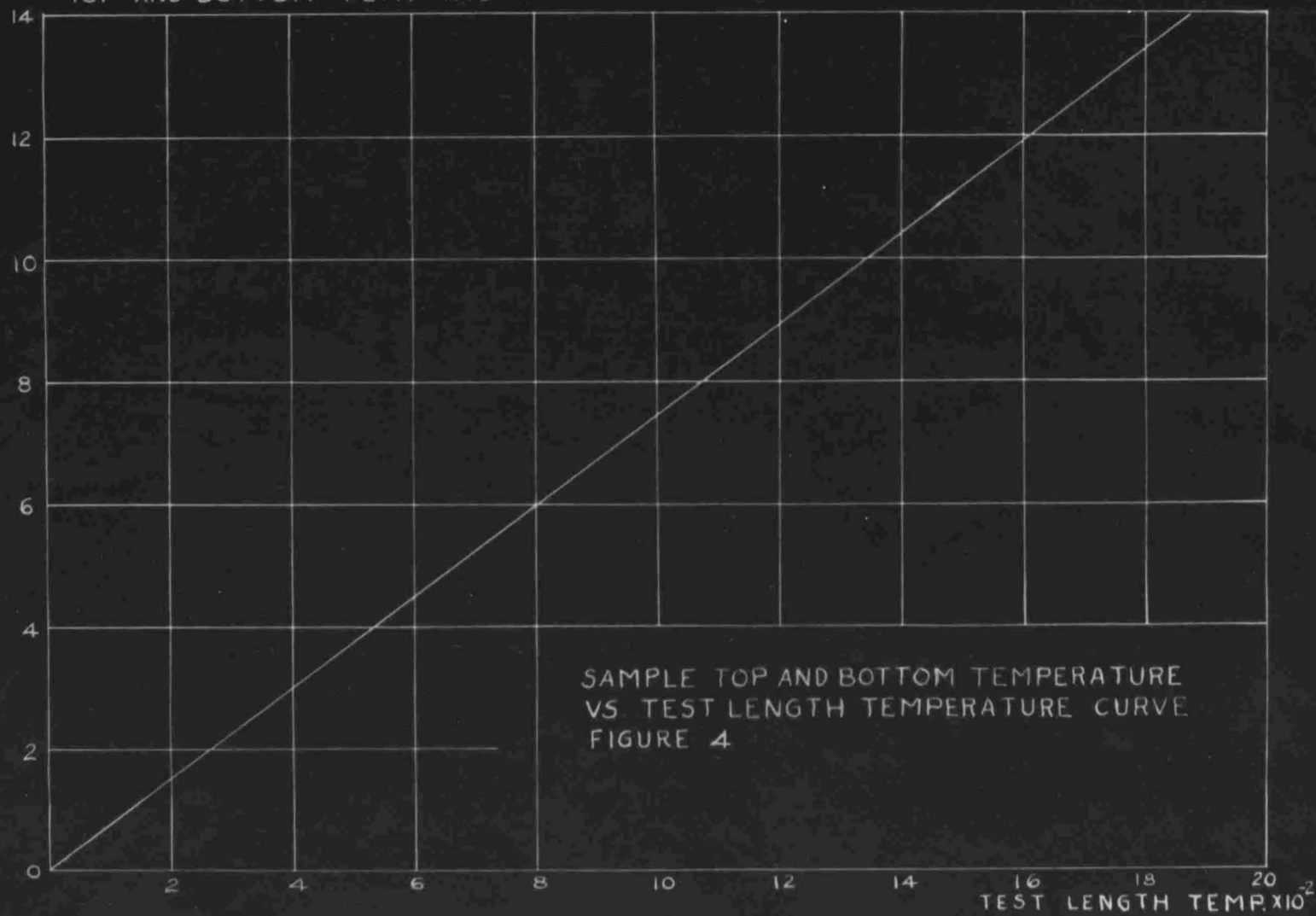
2 Furnace Temperature Control

Furnace temperature control is maintained by means of three thermocouples, a control box, and an automatic temperature recorder. There is one thermocouple placed at each end of the specimen (by means of the thermocouple inlets in the adapters) and the control thermocouple placed just outside the alundum liner near the heating element. In the following discussion, figures 2, 3, and 4 should be referred to.

Each furnace has a control box which consists of a galvanometer and temperature setting dial. The temperature that is set opposite the index of the temperature setting dial is the temperature that the control box will maintain at the thermocouple located outside the alundum cylinder near the heating element. This control thermocouple actuates the galvanometer in the control box. Every five seconds the control bar drops and stays down for five seconds. If the galvanometer needle is on the low part of the scale the bar, while down, closes the electrical contact that shunts the slide wire rheostat resulting in greater voltage drop across the heating coils. When the temperature has risen sufficiently so that the galvanometer needle reads high or neutral, the



TOP AND BOTTOM TEMP $\times 10^{-2}$



SAMPLE TOP AND BOTTOM TEMPERATURE
VS. TEST LENGTH TEMPERATURE CURVE
FIGURE 4

bar will not depress the galvanometer needle, the contact will remain open and there will be less voltage drop across the heating coils by virtue of the slide wire rheostat resistance.

The temperature at the control thermocouple, because it is nearer the heating element will be at a considerably higher temperature than the thermocouples in the top and bottom of the specimen. The thermocouples at the top and bottom of the specimen are cooler than the portion of the specimen actually under test. Furthermore the upper thermocouple tends to become hotter than the lower one. The next paragraphs will show how this variety of temperature conditions is utilized to give a uniform desired temperature to the part of the specimen between the specimen holding points.

The manner in which the temperatures of the top and bottom of the furnace are equalized can be shown by reference to the heating element electric wiring diagram. Without the drum type resistance in the upper heating element part of the circuit, the top would become hotter. The top and bottom temperatures are automatically recorded. If the top temperature is too high, resistance is cut in causing a smaller voltage drop across the top heating coils, until the top temperature records the same temperature as the bottom.

For each furnace and for each material a test is run to determine the relationship between the top and bottom temperature and the part of the specimen under test. Besides the top and bottom thermocouples, for this test only, three thermocouples are placed internally in the test portion of

the specimen. The drum resistance is adjusted so top and bottom read the same. The three temperatures recorded from the thermocouples in the test portion of the specimen are invariably the same. For a number of furnace temperatures there are recorded top and bottom temperatures versus specimen temperatures. This information in the form of a curve is shown in figure 4. For any given test temperature the curves will yield a top and bottom temperature which can be maintained by proper use of the temperature setting dial and the drum type resistance.

III THE DIMENSIONAL ANALYSIS APPROACH

The purpose of the dimensional analysis approach was to attempt to find a relationship between time, initial stress, and stress, so that for a given material suitable values could be substituted in the expression to give the stress at any time.

Eight variables were considered, and the mass(M), length (L), time(T), temperature(θ) system of dimensions was used as shown below.

<u>Variable</u>	<u>Symbol</u>	<u>Dimensional Formula</u>
Initial stress	σ_0	$M L^{-1} T^{-2}$
Stress	σ	$M L^{-1} T^{-2}$
Young's Modulus	E	$M L^{-1} T^{-2}$
Variation of Young's Modulus with temp- erature	ϵ	$M L^{-1} T^{-2} \theta^{-1}$
Coefficient of ther- mal expansion	α	θ^{-1}
Time	T	T
Temperature	θ	θ
$\frac{d(\frac{\sigma}{E})}{d\theta}$	β	$M L^{-1} T^{-2} \theta^{-1}$

The function of the variables is written as a dimensionless quantity.

$$\Phi(\sigma, E, \epsilon, T, \sigma_0, \theta, \alpha, \beta) = M^0 L^0 T^0 \theta^0 \quad (1)$$

Changing the form gives

$$(M\bar{L}\bar{T})^a (M\bar{L}\bar{T})^b (M\bar{L}\bar{T}\bar{\theta})^c (T)^d (M\bar{L}\bar{T})^e (\theta)^f (\theta)^g (M\bar{L}\bar{T}\bar{\theta})^h = M^{\circ} L^{\circ} T^{\circ} \theta^{\circ} \quad (2)$$

and finally

$$M^{a+b+c+e+h} L^{-a-b-c-e-h} T^{-2a-2b-2c+d-2e-3h} \theta^{-c+f-g-h} = M^{\circ} L^{\circ} T^{\circ} \theta^{\circ} \quad (3)$$

Equating exponents to zero gives the following simultaneous linear equations:

$$a + b + c + e + h = 0 \quad (4)$$

$$-a - b - c - e - h = 0 \quad (5)$$

$$-2a - 2b - 2c + d - 2e - 3h = 0 \quad (6)$$

$$-c + f - g - h = 0 \quad (7)$$

It is observed that equations (4) and (5) are not independent. There are then 3 independent equations involving the 8 unknowns. The method used to find the dimensionless parameters is that suggested by Sohoni(3)* in his "Engineering Mathematics".

Of the eight unknowns in equations (4), (6), and (7), b, f, and d are solved for in terms of a, c, e, g, and h giving

$$b = -a - c - h - e \quad (8)$$

$$f = c + g + h \quad (9)$$

$$d = h \quad (10)$$

*Bracketed numbers refer to bibliography.

A table of trials is set up. For each trial arbitrary values are assigned to a, c, e, g, and h. Substituting these values into (8), (9), and (10) values for b, f, and d are obtained. On trial 1, h is given a value of 1, while a, c, e, and g are set equal to zero. b is found equal to -1, d is equal to +1, and f is equal to +1, giving π_1 a value of $\frac{\theta \beta T}{E}$. The following table shows 5 trials with the resulting π_1 term for each trial.

Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
a = 0	a = +1	a = 0	a = 0	a = 0
b = -1	b = -1	b = -1	b = -1	b = 0
c = 0	c = 0	c = +1	c = 0	c = 0
d = +1	d = 0	d = 0	d = 0	d = 0
e = 0	e = 0	e = 0	e = +1	e = 0
f = +1	f = 0	f = +1	f = 0	f = +1
g = 0	g = 0	g = 0	g = 0	g = +1
h = +1	h = 0	h = 0	h = 0	h = 0
$\frac{\theta \beta T}{E}$	$\frac{\sigma}{E}$	Figure 5	$\frac{\epsilon \theta}{E}$	$\theta \alpha$

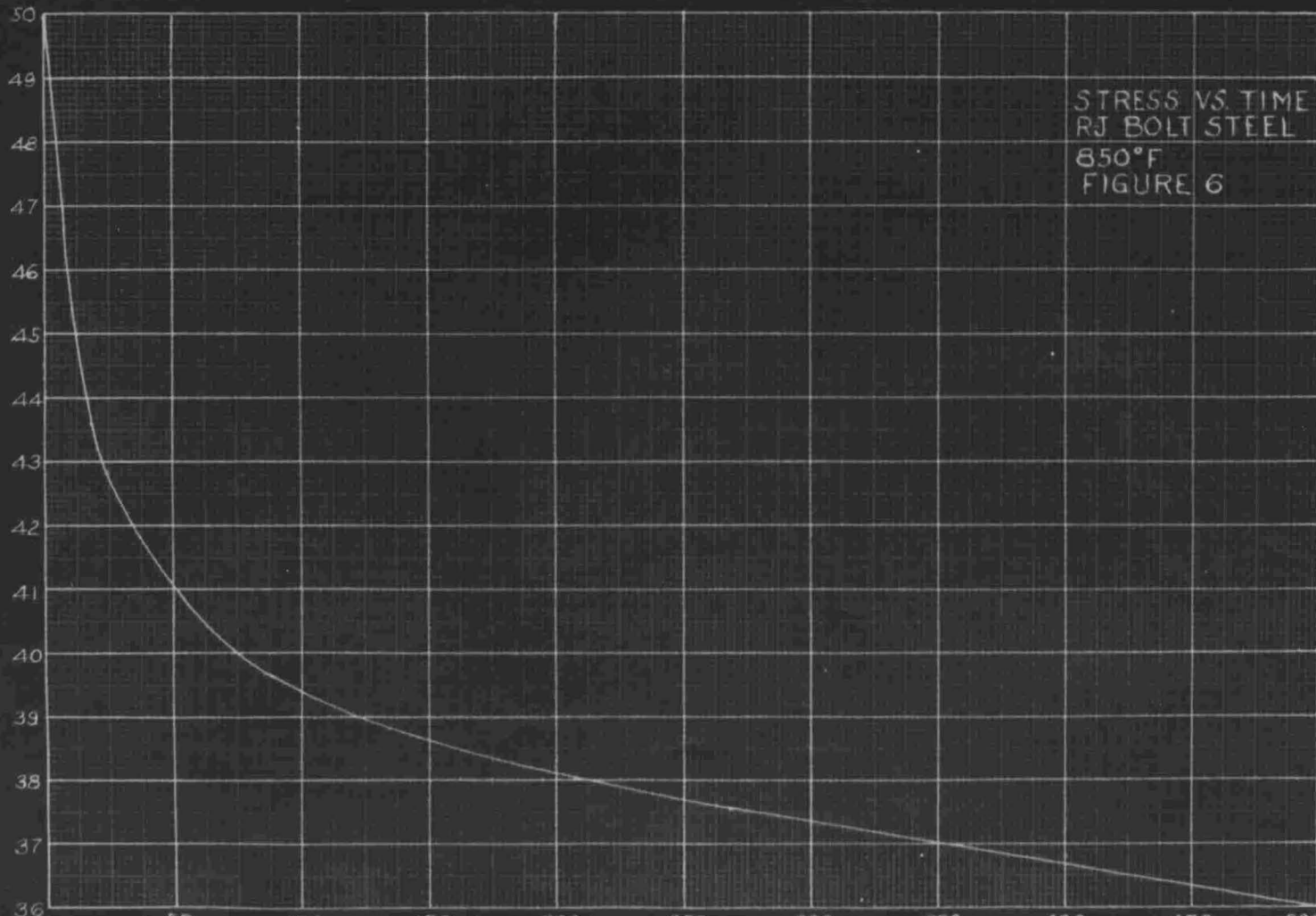
These 5 π_1 terms are combined to give 4 π_1 terms $\pi_1 = \frac{\sigma}{E}$, $\pi_2 = \frac{\epsilon}{E \alpha}$, $\pi_3 = \frac{\beta T}{\sigma_0 \alpha}$, $\pi_4 = \frac{\epsilon \theta}{\sigma_0}$, considered to be in a more useful form than the original ones. As σ appears only in π_1 , the plan was to select several metals and for each substitute values of the variables in order to plot π_1 against each of the other π_1 terms. It was hoped that a mathematical expression for each of the curves could be found, yielding an expression for stress possibly having the form:

$$\sigma = \frac{E}{3} \left[f_1(\pi_2) + f_2(\pi_3) + f_3(\pi_4) \right] \quad (11)$$

The metals selected were RJ (see figure 14 for the metal's composition and properties) and RY. These are low alloy steels and possess relaxation properties quite inferior to the high alloy steels. The relaxation curves of all the metals studied are somewhat difficult to analyze since most of the relaxation occurs during the first few hours of the test; the stress-time curve is somewhat hyperbolic in nature. The high alloy steels possess the characteristic of rapid initial relaxation to a more marked degree than do the low alloy steels. For this reason low alloy steels were selected for analysis.

Three tests were made on RJ, the first with an initial stress of 50,000 p.s.i. at 850° F, the second with an initial stress of 30,000 p.s.i. at 950° F, the third with an initial stress of 25,000 p.s.i. at 1000° F. Stress versus time curves were drawn for the 3 runs for times up to 500 hours. Of the variables used the most difficult of obtaining was β . It was hoped that it would be a constant, such as the specific heat of water is nearly a constant for all conditions. The slopes of the stress-time curves were taken from the 3 curves at frequent intervals (see figure 16). Thus for time equal to 25 hours $\frac{\Delta\sigma}{\Delta t}$ equaled 88, 114, and 88 for temperatures of 850° F, 950° F, and 1000° F respectively. β was found by taking the difference between $\frac{\Delta\sigma}{\Delta t}$ of 850° F and 950° F and dividing by the temperature difference. This gave a β of .026 between tem-

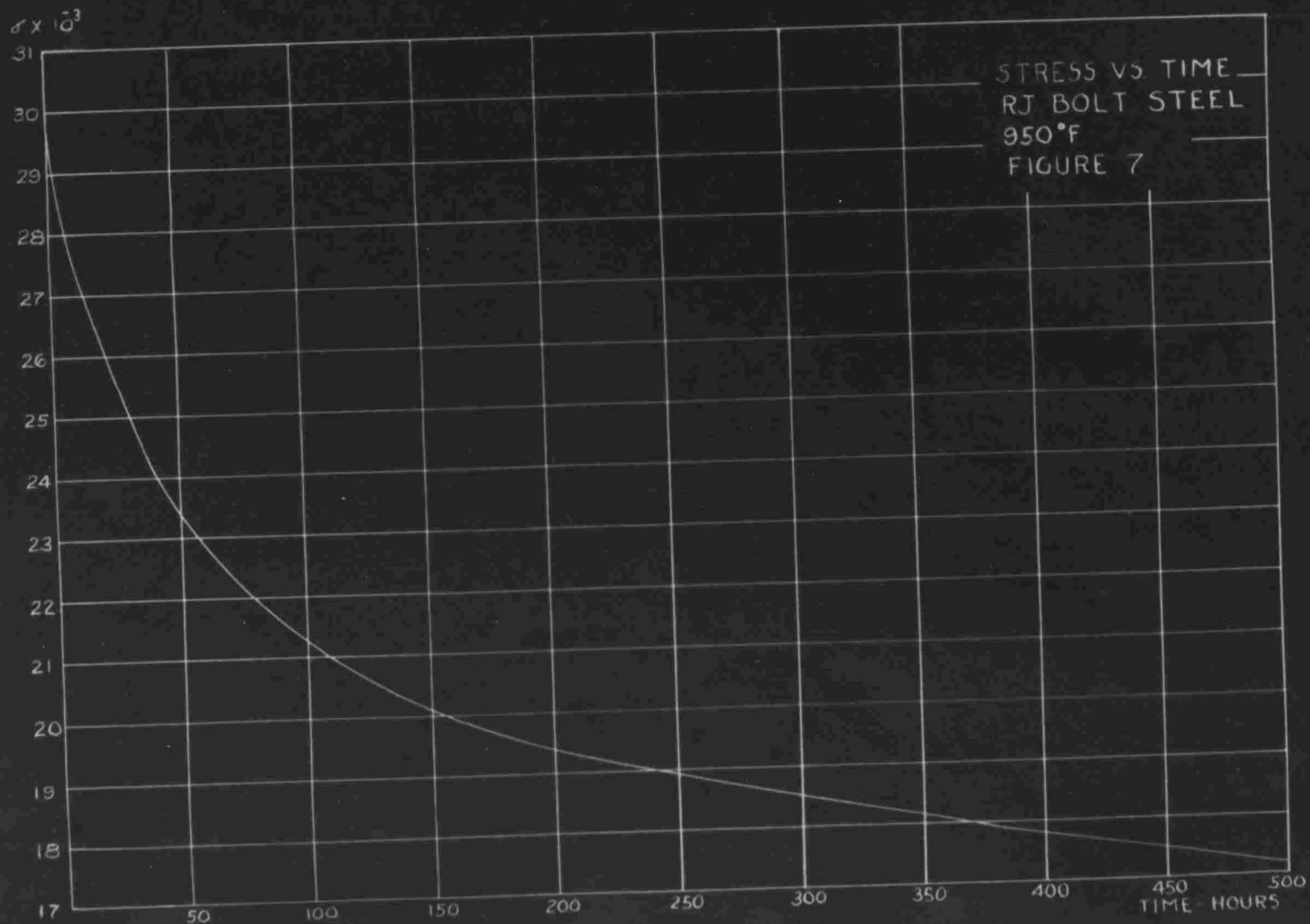
$\sigma \times 10^3$



STRESS VS. TIME
RJ BOLT STEEL
850°F
FIGURE 6

14

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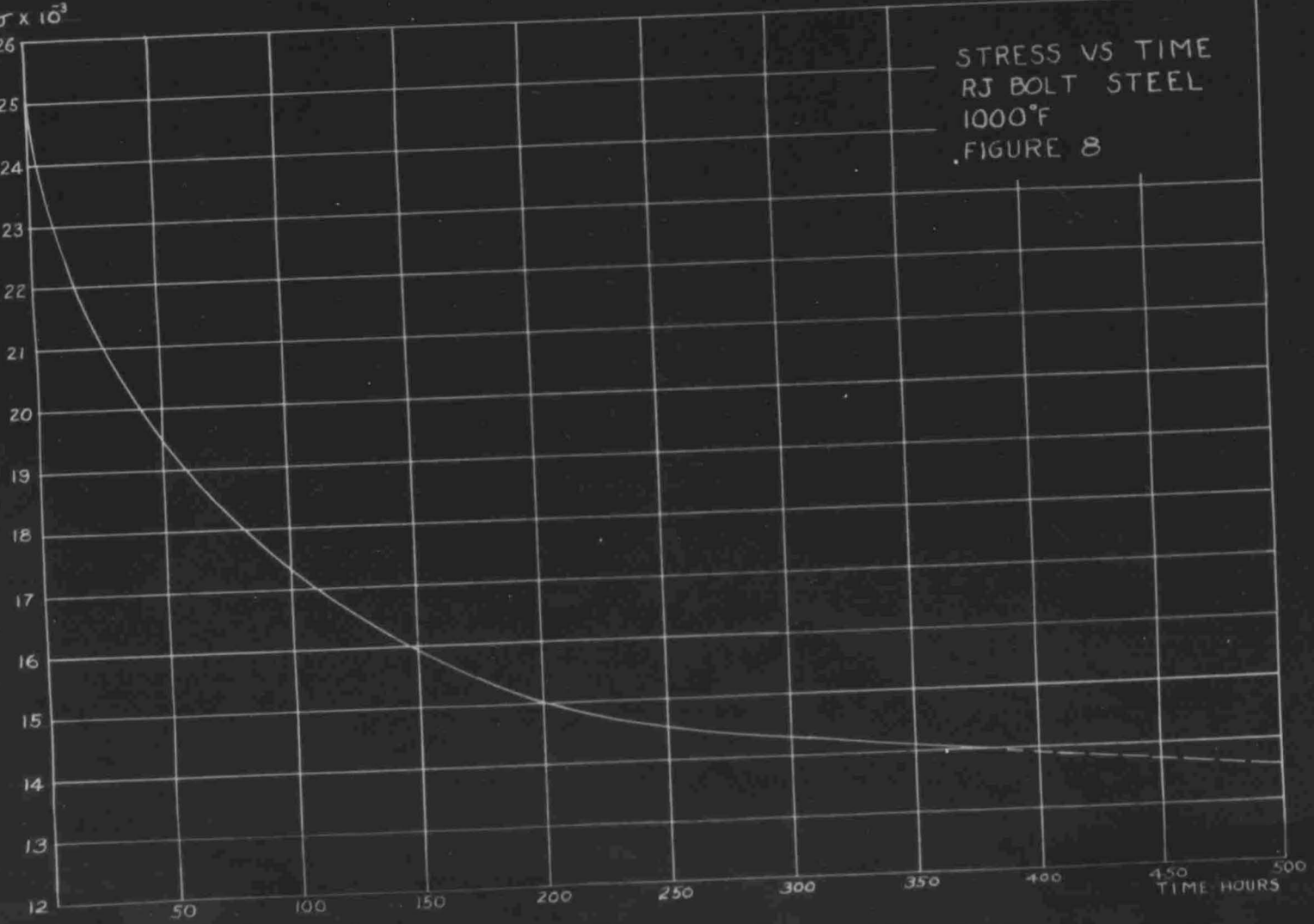


$\sigma \times 10^3$

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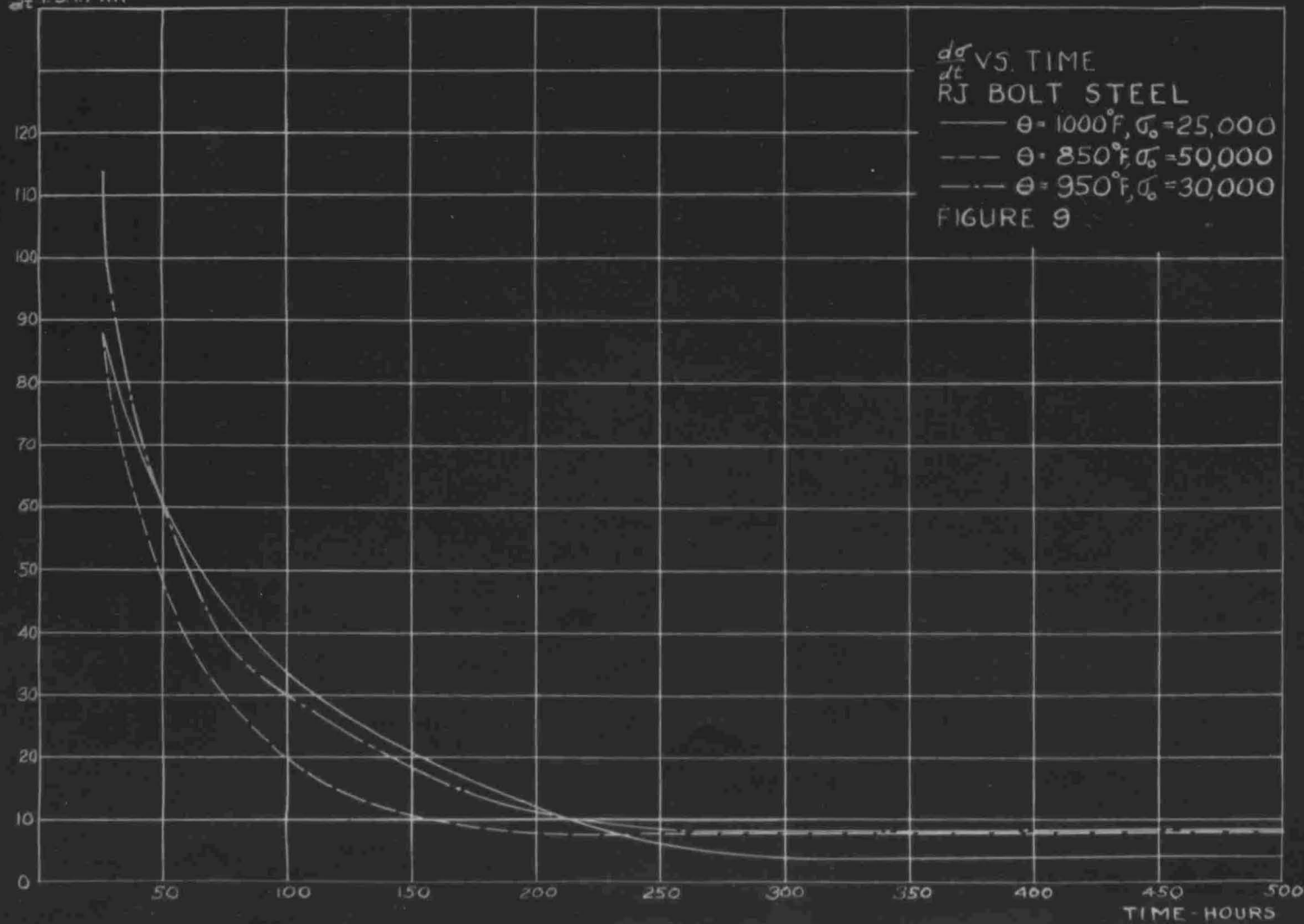
STRESS VS TIME
RJ BOLT STEEL
1000°F
FIGURE 8

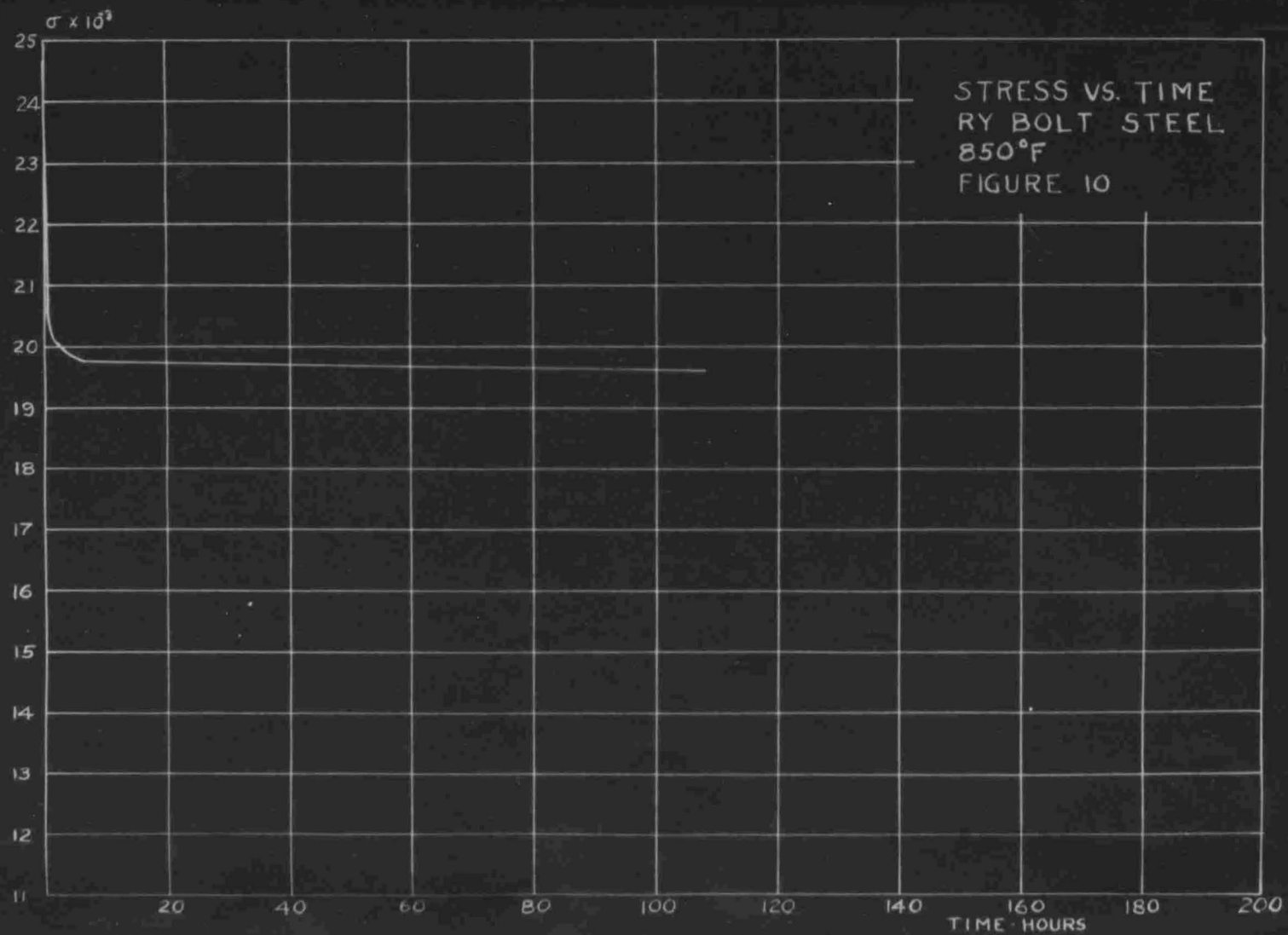
50 100 150 200 250 300 350 400 450 500
TIME HOURS

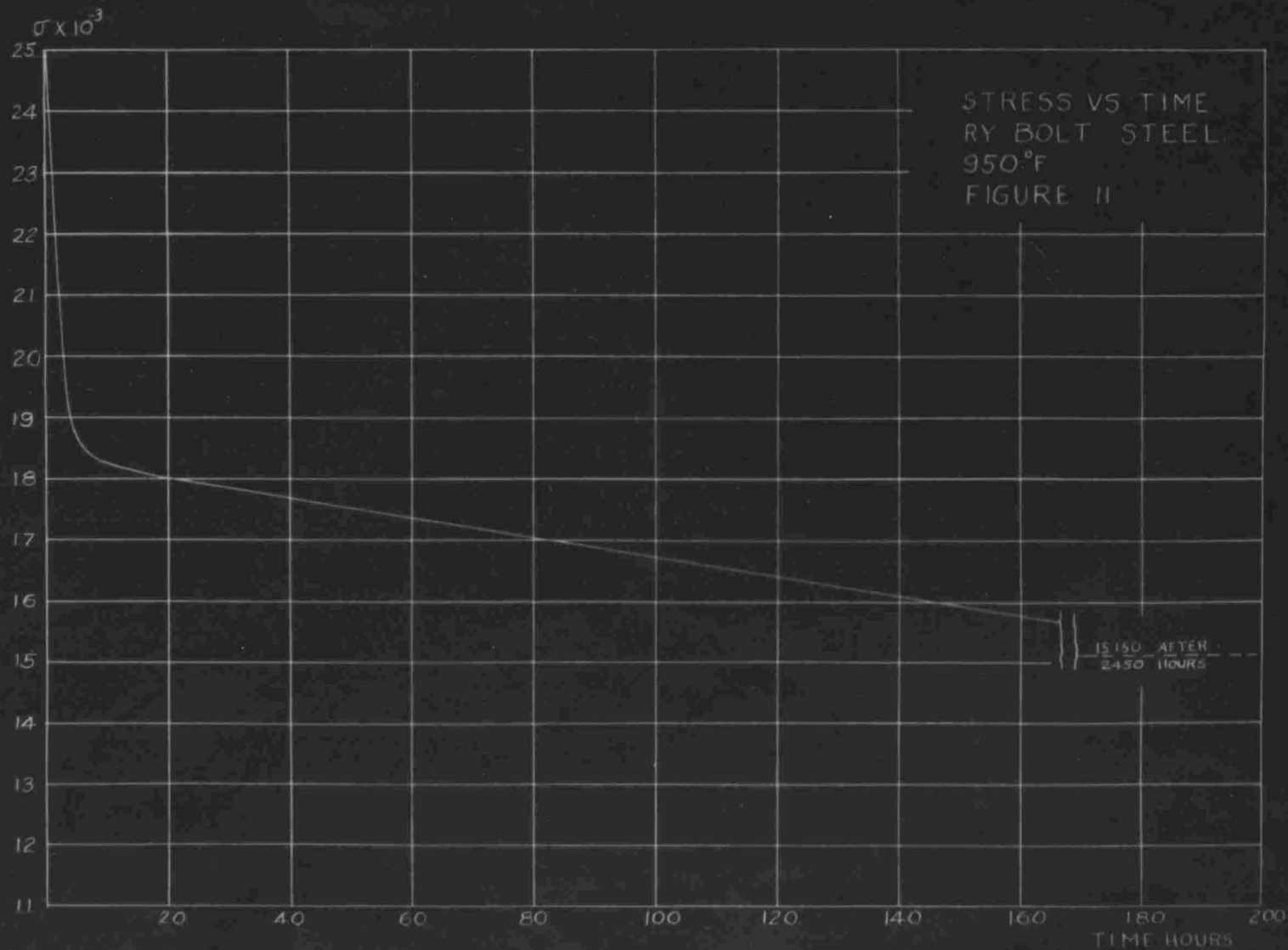


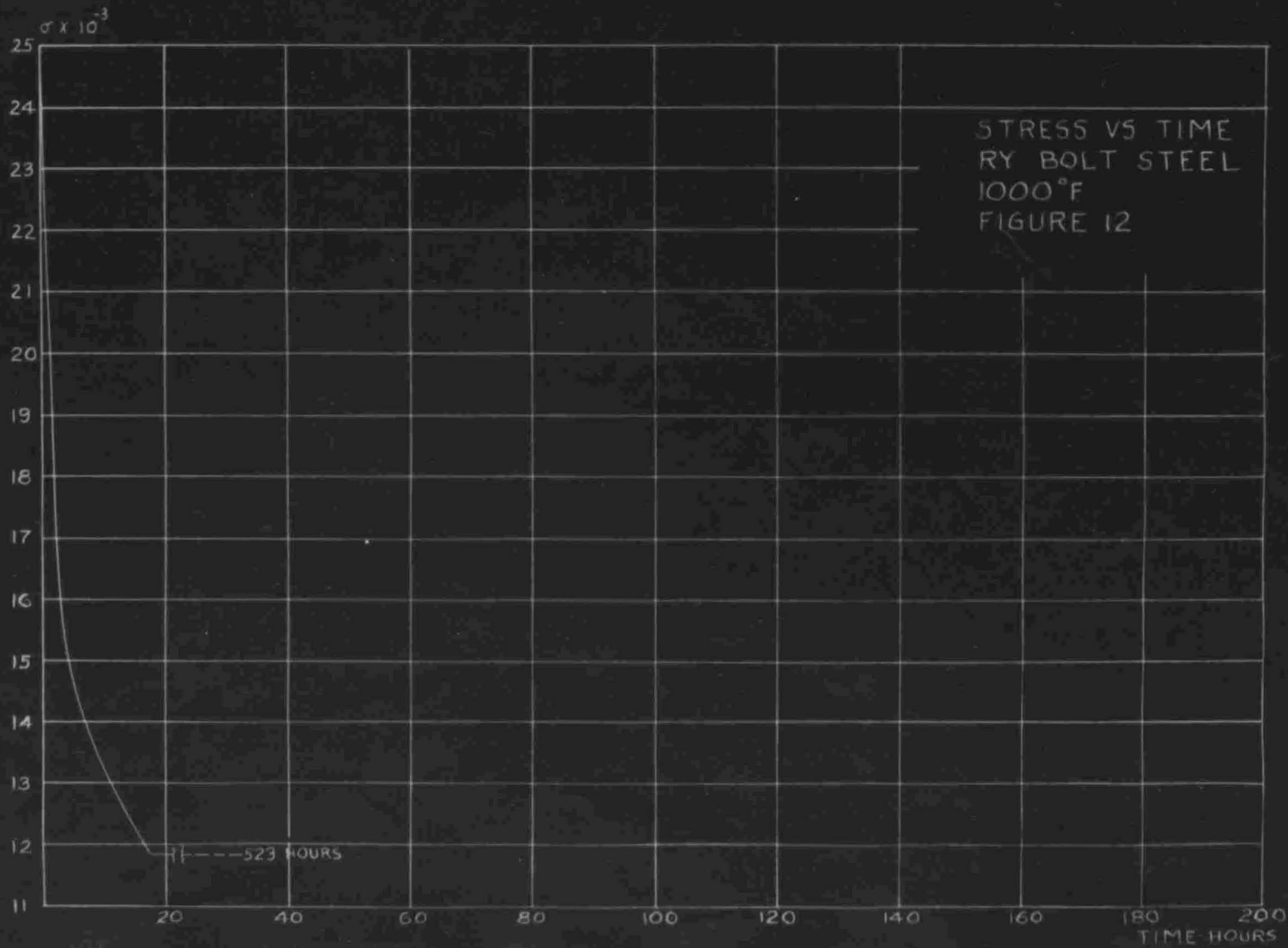
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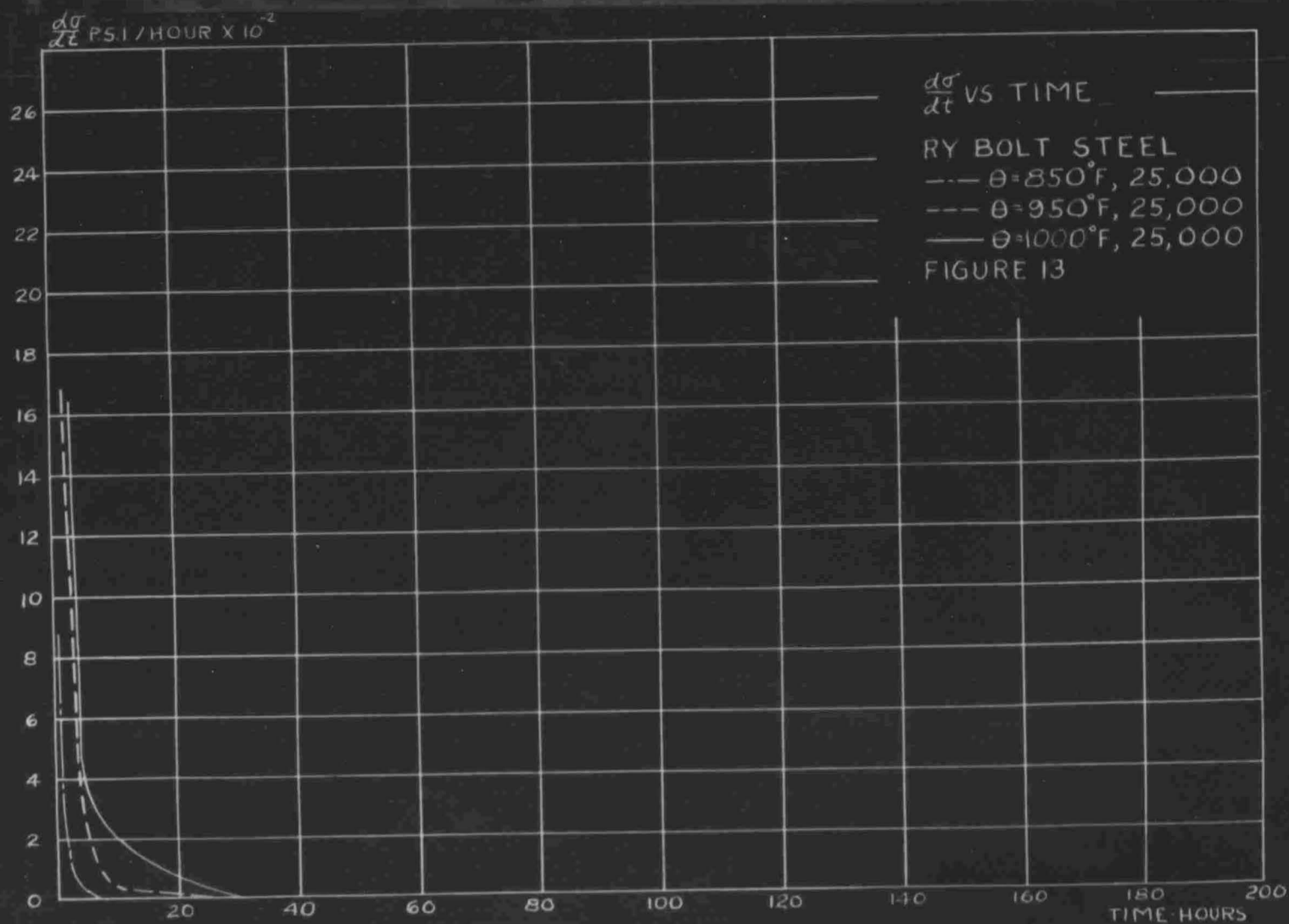
$\frac{d\sigma}{dt}$ P.S.I./HR



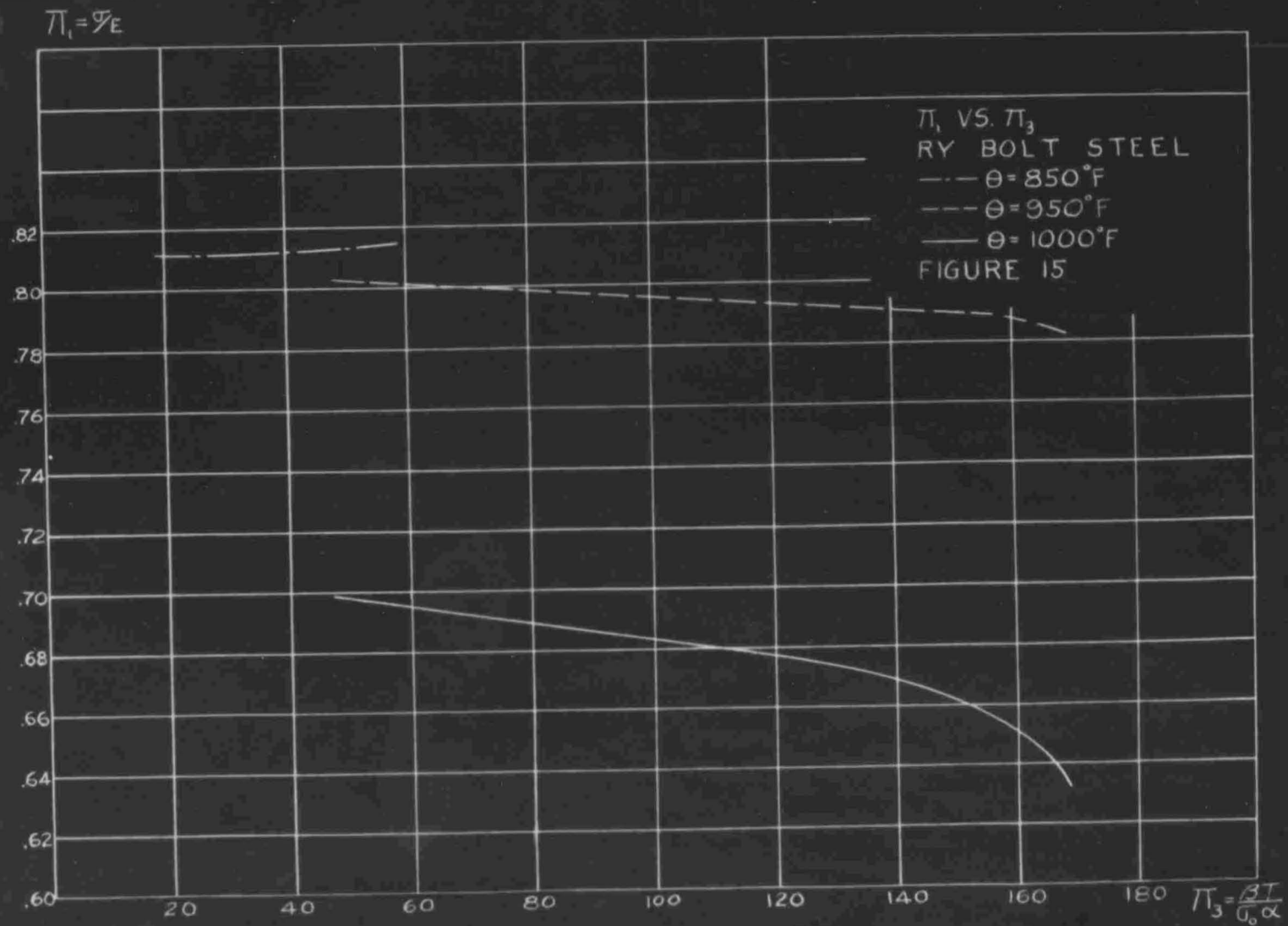








	C	S	P	Mn	Si	Cr	Mo	Ni	V	W	ULT. STR.	% ELONG.
RJ	.48	.01	.008	.23	.23	1.32			.28	1.78	233 500	
RX	.16	.016	.02	.63	.24		.53				57 500	36.7
ZR	.33	.02	.045	.63	.28	.09	.44	2.7			102 400	
SA	.29	.012	.012	.48	.75	1.22	.50		.23		122 300	15.5
RY	.44	.01	.016	.58	.78	1.21	.53		.23		124 850	22.4
QWA	.38	.01	.012	.64	.19	1.02	.48		.24		144 950	17.8
QW	.38	.014	.006	.66	.22	.96	.49		.28		113 700	23.0
QV	.39	.05	.021	.76	.25	.38	.59			1.08	121 750	19.0
QVA	.38	.02	.02	.76	.24	.63	.6			1.19	129 100	21.8
HT	.11	.02	.01	.36		12.78		.01			98 500	23.5
						BOLT STEEL PROPERTIES FIGURE 14						



	$\Theta = 850^{\circ}\text{F}$			$\Theta = 950^{\circ}\text{F}$			$\Theta = 1000^{\circ}\text{F}$				
T	$\Delta\sigma$	ΔT	$\frac{d\sigma}{dT}$	$\Delta\sigma$	ΔT	$\frac{d\sigma}{dT}$	$\Delta\sigma$	ΔT	$\frac{d\sigma}{dT}$	$_{850}\beta_{950}$	$_{950}\beta_{1000}$
25	2200	25	88	2850	25	114	2200	25	88	+0.026	-0.052
50	1200	25	48	1520	25	60.8	1550	25	62	+0.012	+0.004
75	750	25	30	950	25	38	1040	25	41.6	+0.008	+0.007
100	500	25	20	750	25	30	850	25	34	+0.010	+0.008
125	350	25	14	600	25	24	700	25	28	+0.010	+0.008
150	290	25	11.6	450	25	18	560	25	22.4	+0.006	+0.008
175	250	25	10	350	25	14	500	25	20	+0.004	+0.012
200	210	25	8.4	280	25	11.2	330	25	13.2	+0.003	+0.004
225	210	25	8.4	230	25	9.2	210	25	8.4	+0.0008	-0.0008
250	200	25	8.0	210	25	8.4	180	25	7.2	+0.0004	-0.0012
300	190	25	7.6	200	25	8.0	100	25	4	+0.0004	-0.0008
400	190	25	7.6	190	25	7.6	100	25	4	0	-0.007
500	180	25	7.2	180	25	7.2	100	25	4	0	-0.006
						RJ BOLT STEEL B COMPUTATION DATA FIGURE 16					

$\Theta = 850^{\circ}\text{F}$					$\Theta = 950^{\circ}\text{F}$					$\Theta = 1000^{\circ}\text{F}$				
σ	T		$\frac{\Delta\sigma}{\Delta t}$	T	σ	T		$\frac{\Delta\sigma}{\Delta t}$	T	σ	T		$\frac{\Delta\sigma}{\Delta t}$	T
25000	0		11000	.3	25000	0		2480	1.0	25000	0		4800	.5
21700	.3		420	1.0	22192	.5		2300	2.0	23630	.3		2046	3.0
20234	.7		160	2.0	21009	2.75		2300	3.0	20835	.8		340	5.0
20234	1.0		105	3.0	19073	3.75		570	4.0	19823	1.1		265	7.0
20133	1.8		55	4.0	18284	5.5		250	5.0	16421	2.2		220	10.0
19781	3.3		25	5.0	18028	27.0		130	6.0	15800	3.6		165	15.0
19776	6.2		18	6.0	17794	28.0		70	7.0	14640	4.6		150	17.5
19776	9.3		8	7.0	17368	77.5		55	8.0	14274	5.6		0	17.6
19776	17.4		2	8.0	16953	82.5		45	9.0	14274	6.6			
19776	26.8		2	9.0	16953	94.5		39	10.0	13523	7.8			
19773	29.6		2	10.0	16878	96.5		33	12.0	13523	8.6			
19770	33.2				15132	166.3		24	15.0	13523	9.6			
19767	47.5				15132	245.0		15	20.0	13019	11.6			
19767	106.3							15	160.0	12452	12.6			
19761	108.2									12452	13.6			
19761	189.3									12452	14.6			
										12263	16.0			
										11828	17.6			
										11828	523.0			
										RY STRESS TIME DATA FIGURE 17				

T	$\frac{d\sigma}{dt}(850^\circ\text{F})$	$\frac{d\sigma}{dt}(950^\circ\text{F})$	$\frac{d\sigma}{dt}(1000^\circ\text{F})$	$_{850}\beta_{950}$	$_{950}\beta_{1000}$
5.0	25	250	340	2.25	1.8
6.0	18	130	310	1.12	3.6
7.0	8	70	265	.62	3.9
8.0	2	55	242	.53	3.74
9.0	2	45	220	.43	3.50
10.0	2	39	200	.37	3.22
RY BOLT STEEL β COMPUTATION DATA FIGURE 18					

T	σ	$E \times 10^{-6}$	σ_o	θ	$\alpha \times 10^6$	β	$\pi_1 = \frac{\sigma}{E}$	$\pi_3 = \frac{\beta T}{\sigma_o \alpha}$
5.0	18 700	23.3	25 000	950	7.6	1.8	.803	47.25
6.0	18 500	23.3	25 000	950	7.6	3.6	.794	113.5
7.0	18 400	23.3	25 000	950	7.6	3.9	.790	143.5
8.0	18 350	23.3	25 000	950	7.6	3.74	.788	157.0
9.0	18 300	23.3	25 000	950	7.6	3.5	.785	165.0
10.0	18 250	23.3	25 000	950	7.6	3.22	.783	169.0
5.0	14 650	21.0	25 000	1000	7.6	1.8	.698	47.25
6.0	14 250	21.0	25 000	1000	7.6	3.6	.679	113.5
7.0	13 990	21.0	25 000	1000	7.6	3.9	.666	143.5
8.0	13 710	21.0	25 000	1000	7.6	3.74	.654	157.0
9.0	13 450	21.0	25 000	1000	7.6	3.5	.641	165.0
10.0	13 220	21.0	25 000	1000	7.6	3.22	.630	169.0
5.0	19 800	24.3	25 000	850	7.6	2.25	.815	59.25
6.0	19 770	24.3	25 000	850	7.6	1.12	.813	35.4
7.0	19 770	24.3	25 000	850	7.6	.62	.813	22.9
8.0	19 770	24.3	25 000	850	7.6	.53	.813	22.3
9.0	19 770	24.3	25 000	850	7.6	.43	.813	20.35
10.0	19 770	24.3	25 000	850	7.6	.37	.813	19.45
					RY BOLT STEEL PI TERM COMPUTATION FIGURE 19			

peratures of 850° F and 950° F, and a value of .052 (opposite sign) between 950° F and 1000° F. Other values of β were computed, and curves of $\frac{d\sigma}{dT}$ versus time were drawn. The crossing of the curves was disappointing, and indicated that a different attack was necessary.

The next metal selected was RY. It was thought that the crossing of the $\frac{d\sigma}{dT}$ curves was caused by the fact that the curves had three different initial stresses. It was decided that the effect of initial stress would in these runs be avoided by starting them all at 25,000 p.s.i. using the same 3 temperatures 850° F, 950° F, and 1000° F.

The same procedure of curve plotting and computing was used in the case of RY as RJ. The difficulty of crossing curves was not encountered. However values for β were found to be quite different. From figure 18 it can be seen that for time equal to 8 hours β equaled .53 computed between 850° F and 950° F and equaled 3.74 computed between 950° F and 1000° F. This is unfortunate as it indicates either that β varies considerably with temperature, or more likely, that the test equipment is not sensitive enough to give data for this type of analysis. Nevertheless π_1 was plotted against π_3 (see figure 15). This yielded a family of temperature lines. With temperature entering in this manner it is seen that π_1 and π_3 are the only Pi terms needed, as all the important variables are included in them. However the results are obviously not satisfactory because of the short 850° F curve. This is due to the small values of β used in computing its π_3 . If the same values of β were used in plotting the

850° F line that were used in plotting the 950° F and 1000° F lines, the 850° F line would parallel the other two slightly above the 950° F line.

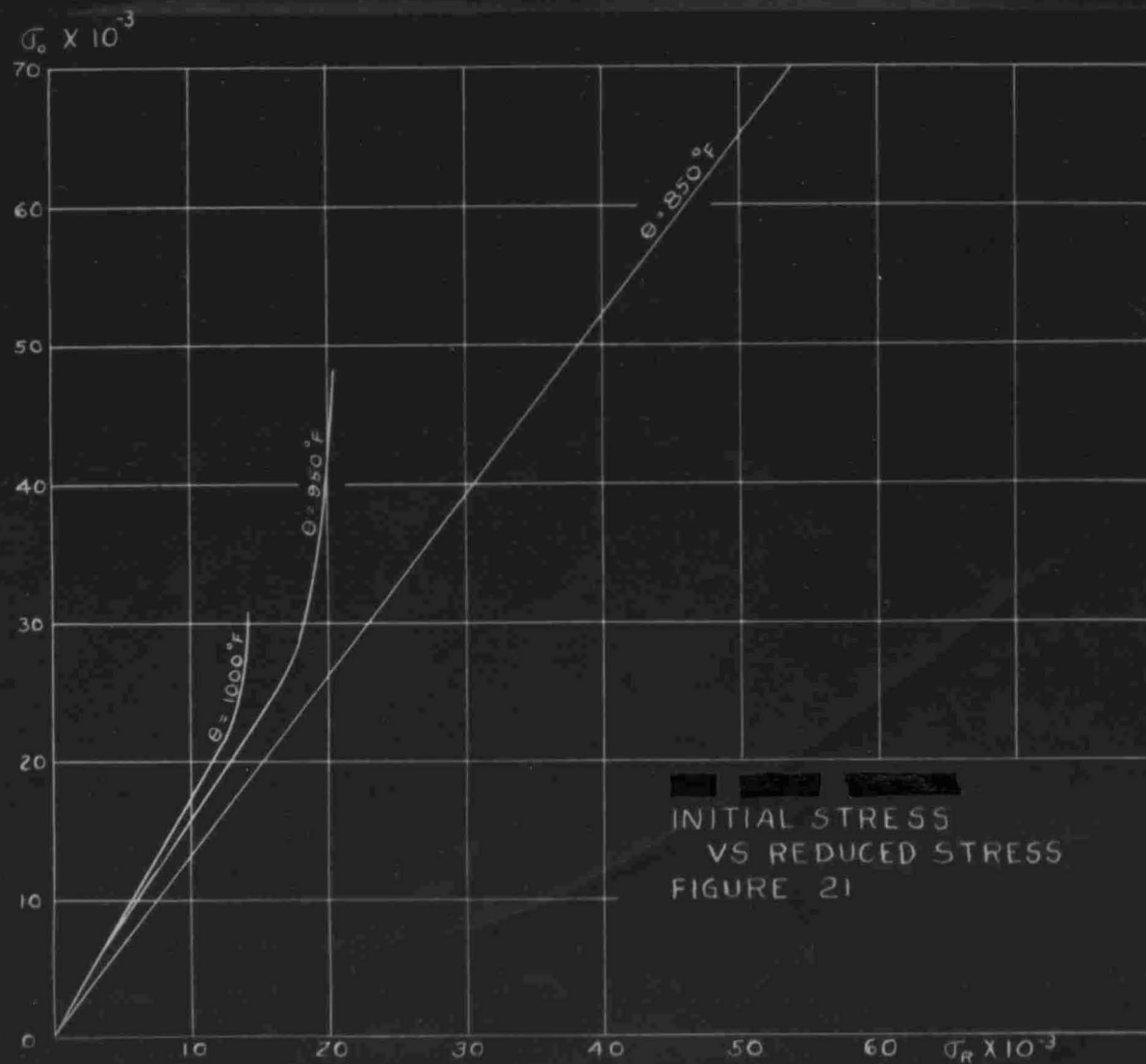
IV TEMPERATURE STRESS CORRELATION

Many of the tests were run until the stress-time curve became essentially parallel to the time axis. It was expected that for a given material the value of stress for which the curve became parallel would be determined by the test temperature. To verify or discount this idea is the purpose of this portion of the thesis.

The first part of the correlation consisted of determining the reduced stress for each test run. Reduced stress is defined as the stress for which the slope of the stress-time curve becomes equal to 2 p.s.i. per hour. 2 p.s.i. was chosen arbitrarily and for no particular reason except that it indicates a very flat curve. Zero slope was not used because a number of tests were not continued until horizontal. Coordinates were set up with initial stress as ordinate and reduced stress as abscissa. Plotting initial stress against reduced stress gave a series of points. As the points did not satisfy straight line, parabola, or exponential conditions, curves were faired by eye thru equitemperature points.

Curve stress differences were obtained for each point by subtracting the reduced stress of the point as plotted from the reduced stress indicated by the faired curve for the same initial stress. Percentage error was obtained by dividing the curve stress difference by its initial stress and multiplying by 100. In fairing the curves, all the values of RX, and the 850° F value of RW were disregarded.

	σ_o	σ_R	θ	STRESS DIFF	%
RY	25 000	15 130	950	870	3.48
RJ	30 000	17 000	950	1 300	4.33
SA	25 000	19 000	950	3 000	8.33
QVA	30 000	20 000	950	1 700	5.68
ZR	25 000	15 000	930	1 000	4.00
QWA	45 000	19 500	950	800	1.78
HT	20 000	11 000	930	2 000	10.0
QVA	30 000	17 600	950	700	2.33
QVA	45 000	20 750	950	750	1.68
RY	25 000	19 700	850	800	3.20
RJ	50 000	36 000	850	2 300	4.60
QW	70 000	56 000	850	3 500	5.00
QWA	50 000	35 500	850	2 800	5.60
RY	25 000	11 800	1000	1 800	7.2
RJ	25 000	13 000	1000	600	2.4
SA	25 000	17 000	1000	3 400	13.6
QWA	30 000	13 000	1000	1 300	4.33
RX	25 000	15 000	850	3 000	12.0
RX	25 000	6 500	950	10 500	42.0
RX	20 000	5 000	1000	6 600	33.0
RW	15 000	4 200	850	7 300	48.7
		<div></div> <div>σ_o AND σ_R CORRELATION DATA</div> <div>FIGURE 20</div>			



The results of the correlation verify the supposition that the test temperature determines the reduced stress. The stress differences and percentage errors do not seem excessive. However the correlation does not mean much for the 1000° F test temperature points because of the limited range of initial stresses used.

V METALLURGICAL FACTORS AFFECTING RELAXATION

The subject metallurgical factors affecting relaxation is one which is still in the process of investigation and much of interest is still expected to be found. To date those factors considered most important are composition, grain size, structure, and variations in manufacturing practice. Each of these factors will be taken up in some detail and illustrated by a comparison of two metals, one having excellent relaxation properties and the other having poor relaxation properties.

It has been found that certain elements when added to steel increase its relaxation resistance. In general they divide themselves into two categories, those that are soluble in iron and those that are said to be carbide forming elements. Examples of the former include nickel, aluminum, silicon, and cobalt. The latter include such elements as tungsten, molybdenum, vanadium, and chromium. The carbide forming elements are considered to have the superior relaxation resisting properties. It is theorized that this property arises from the ability of the carbide particles to wedge themselves in between the slip planes preventing them from slipping.

As regards grain size it has been found that for high temperatures a coarse grain will hold up better than a small, fine grain size.

In grain structure any structure that tends to make the metal soft results in poor relaxation properties. Thus

	Cb	N	C	S	P	Mn	Si	Cr	Mo	Ni	Co	W	ULT.STR	%ELONG	ELASTIC MOD.
RX			.16	.016	.02	.63	.24		.53				57500	36.7	19.4×10^6 AT 1000 °F
UH	1.0	17	.32					21	3	21	21	2	121000	41.0	18.5×10^6 AT 1500 °F

FIGURE 22. COMPARISON OF RX AND UH BOLT MATERIALS

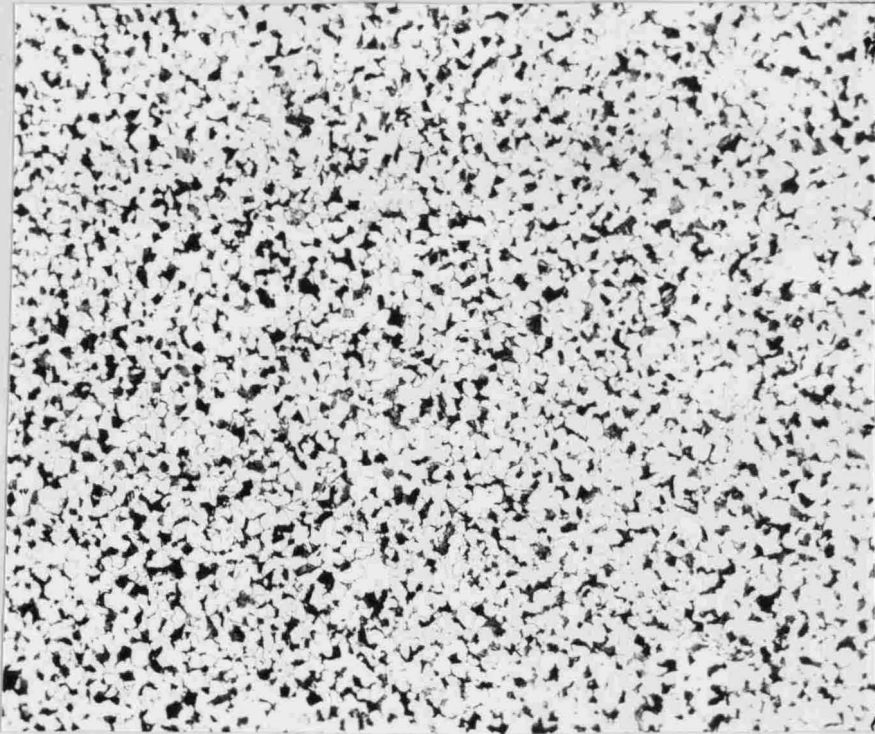


FIGURE 23. RX BOLT STEEL X100

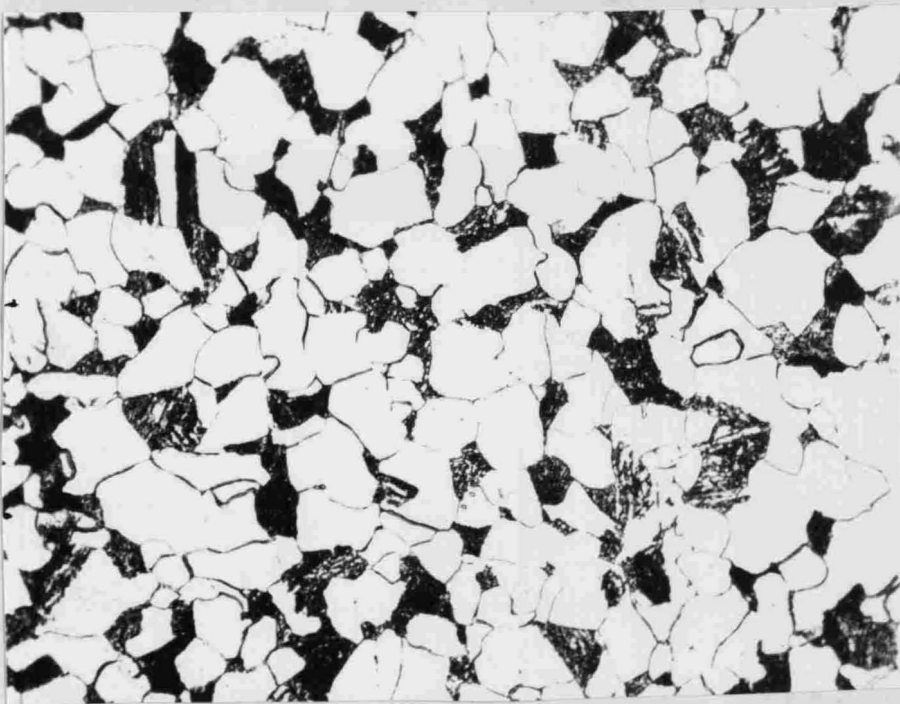


FIGURE 24. RX BOLT STEEL X500

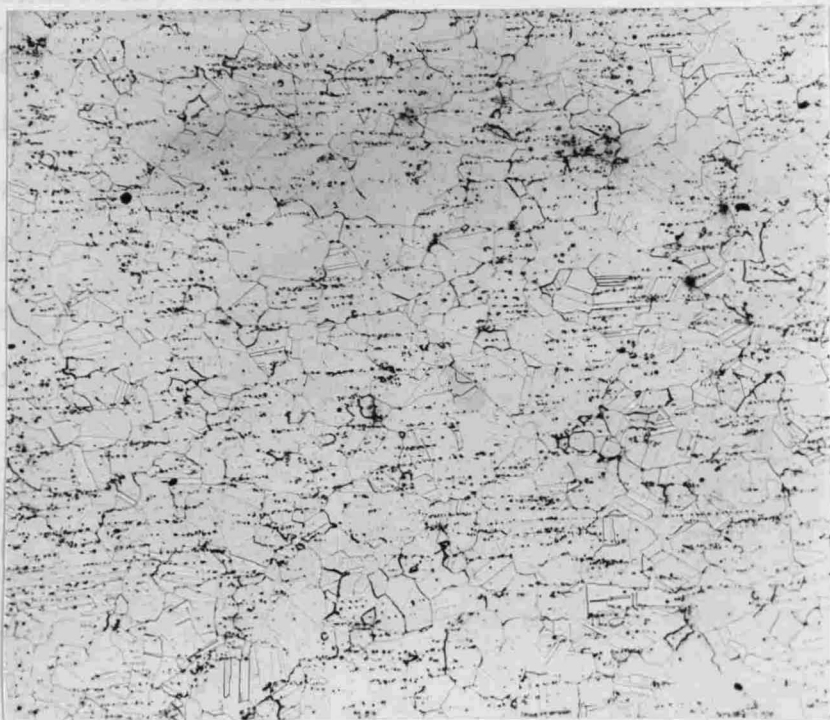


FIGURE 25. UH BOLT STEEL X100

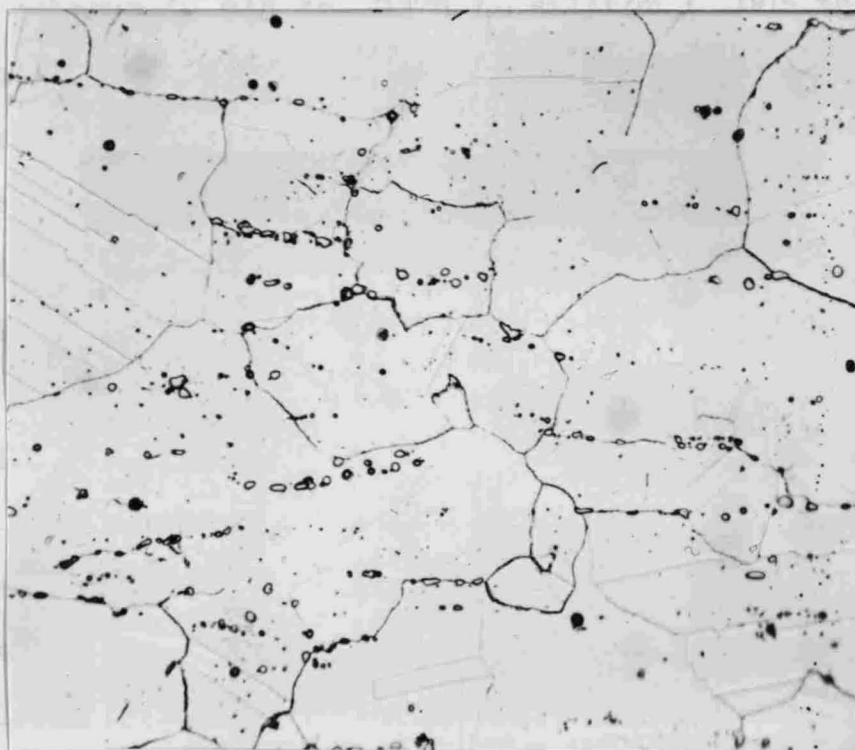


FIGURE 26. UH BOLT STEEL X500

-spheroidization, which causes the iron carbides to form small round spheres is injurious to relaxation resistance. Similarly graphitization in which spheres of graphite are found in the structure also decreases relaxation resistance.

The United States Steel Research Laboratory published in February 1948 a report titled "Effect of Variation in Manufacturing Practice on Creep-Rupture of Low-carbon Steels at 850 F" (4). The report concerns creep tests made on 12 different low carbon, low alloy steels for the purpose of comparing openhearth versus bessemer refinement, aluminum versus silicon deoxidation of steel, and different compositions. Carbon content varied from .07 to .27%. Besides iron and carbon, alloying elements included manganese (.38 to 86%), sulphur (.018 to .037%), silicon (.005 to .23%), aluminum (.002 to .006%), alumina (.002 to .006%), nitrogen (.005 to .22%), and titanium (.001 to .003%).

The results of the tests proved inconclusive as regards bessemer versus openhearth refinement and the effects of composition. The tests did strongly indicate that steel killed with ferrosilicon had higher creep resisting properties than did those killed with aluminum. In evaluating the report it may be said that it has just probed the surface of a very interesting subject.

To illustrate the above described factors RX (K-22) and UH (N155) were selected for comparison. Figure 22 shows a comparison of the two metals. Heat treatment of RX consisted of heating to 1650° F for 1.66 hours followed by furnace cooling. Then heating to 1200° F for 2 hours with air cooling.

Heat treatment of UH consisted of heating to 2200° F for 1 hour with water quenching, followed by aging at 1500° F for 4 hours with furnace cooling.

In comparing the compositions of the metals it is seen that UH has many elements that are soluble in iron or are carbide formers. These include chromium, molybdenum, nickel, cobalt, tungsten, and columbium. On the other hand RX has only a small percentage of molybdenum.

Figures 23 and 24 show photomicrographs of RX at x100 and x500, while figures 25 and 26 show UH at x100 and x500. It is noticed that while the RX grain structure consists of simple ferrite and pearlite, the UH grain structure shows precipitated carbides. It can also be seen that the grains of UH are coarser than those of RX.

The importance of these different characteristics is substantiated by actual test. In a recent relaxation run RX was given an initial stress of 25,000 p.s.i. at 950° F. After 60 hours RX had relaxed to 6350 p.s.i. In another run UH was given an initial stress of 25,000 p.s.i. at 1350° F. After 500 hours UH had relaxed to only 14,000 p.s.i.

VI CONCLUSIONS

In this thesis a relaxation machine has been described, and an attempt has been made to analyze the resulting data to give an expression relating time, temperature, and stress. The analysis showed when two Pi terms, $\frac{\sigma}{E}$ and $\frac{\beta T}{\sigma_0 \alpha}$ were plotted against each other a family of temperature lines resulted. Thus if one had a material for which he desired to know the relaxation stress from a given initial stress after a certain number of hours at temperature Θ , he could evaluate $\frac{\beta T}{\sigma_0 \alpha}$ and from the curve find $\frac{\sigma}{E}$. Multiplying this value of $\frac{\sigma}{E}$ by E would give σ . Unfortunately β was found to vary over a wide range of values, indicating either β varied with temperature or that the test equipment was not sensitive enough to give results suitable for such an analysis.

Several factors may have caused inconsistent results. Any further analysis should insure control of metallurgical treatment of the specimen material. This was discussed under metallurgical factors and emphasized the importance of uniformity in the method of deoxidizing the steel. In these tests metallurgical records were limited to the specimen's heat treatment.

Another source of inconsistent results was the method of placing the load on the specimen. Referring to figure I, the loading was done in two steps. First a wedge was removed supporting loading beam 2. Then the support of the jack screw for beam 1 was removed. Such a system of load application resulted in the load being applied in a slightly different

manner each time. This method of loading also allowed for the possibility that the test initial stress may have been actually larger than that computed from the oil tank load. This followed from the consideration that creep may have already begun by the time the dial on the strain gauge was set presumably .00015 inches greater than the initial elongation. If creep had already started the test initial stress would have been essentially greater than that indicated by the oil tank load. For further analysis it would seem desirable if this system of loading would be replaced by one that would insure short loading time and would apply the load to the specimen in the same manner for each test. If the oil tank were supported by a platform that could be lowered by a motor, these conditions would be met.

In as much as the results of the dimensional analysis approach were not satisfactory, a correlation was made between initial stress and reduced stress for a number of low alloy steels. 17 test runs and 8 different metals were used in the correlation. The curves resulting from the correlation yielded the reduced stress for a given initial stress and temperature. For the 17 runs the average error between values given by the curves and the test results was 5.2% when compared with the initial stresses.

A plan for continuation of the dimensional analysis approach would first of all remedy the above mentioned inconsistencies in the initial conditions of test. A test material should be chosen having slow relaxation properties. It is noted that RJ is superior to RY in this respect. Tests would

be run at a constant initial stress with varying temperatures to establish the nature of β --that is, whether β is a constant or a function of temperature. Without knowing the nature of β it would be impossible to evaluate π_3 for any but tested initial conditions. If the nature of β can be established, a prediction can be made for the stress at a given time for a bolt material having a given initial stress and constant temperature. This prediction would then be verified by test.

The interesting subject of reloading of the bolt was not included in the project. Tests showed that reloading the specimen to the initial stress results in greater relaxation resistance. This is attributed to the hotwork produced by the previous run. Factors affecting the amount of relaxation would be test temperature, time of rest at no load, and length of time interval between reloadings.

It is noted that the relaxation test as described in this thesis differs from the actual bolt behavior in that the actual bolt has its load applied at room temperature, while the test specimen has its load applied at the test temperature. A further project would be the design of a relaxation machine to investigate the affect of this initial temperature rise on the loaded bolt. It would require allowance for the differences in the coefficients of expansion of the bolt and flange materials.

In conclusion it is stated that the theories and relationships expressed here require further experimental support. However it is the belief of the author that the

project has indicated the direction for further analyses to determine a relationship between time, initial stress, and stress.

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APPENDIX I

Let ϵ' = elastic strain

ϵ'' = plastic strain

ϵ = total strain

σ_0 = initial stress

σ = stress

E = Young's Modulus

$$\epsilon' + \epsilon'' = \epsilon = \frac{\sigma_0}{E}^*$$

$$\epsilon' = \frac{\sigma}{E}$$

$$\epsilon'' = \frac{1}{E} [\sigma_0 - \sigma]$$

Therefore the plastic strain is equal to a constant times relaxation.

*Basic equation from Relaxation of Metals at High Temperatures by Trumpler(5).